Anomalous X-ray pulsars and soft gamma-ray repeaters in supernova remnants

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Abstract. I consider the state of play regarding associations of supernova remnants (SNRs) with anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs). The three AXP/SNR associations are convincing, and are consistent with AXPs being young, low-velocity neutron stars. The three SGR/SNR associations are far more likely to be chance superpositions, and rely on SGRs being high velocity (>1000 km s^{-1}) objects. These results imply either that AXPs evolve into SGRs, or that SGRs and AXPs represent different populations of object.

1. Introduction

The recent detection of rapidly slowing $\sim$6-second pulsations from soft gamma-ray repeaters (SGRs) makes a strong argument that these sources are *"magnetars"*, isolated neutron stars with inferred dipole magnetic fields $B \sim 10^{14} - 10^{15}$ G (e.g. Kouveliotou et al. 1998).

Thompson & Duncan (1996) have noted that the emergent class of six *"anomalous X-ray pulsars"* (AXPs; van Paradijs et al. 1995) are strikingly similar to SGRs in their periods, period derivatives, X-ray luminosities, X-ray spectra, lack of evidence for binarity and coincidence with supernova remnants (SNRs). They thus propose that AXPs, like SGRs, are magnetars. In the subsequent few years, several more AXPs and SGRs have been discovered, several of which are near or in SNRs (e.g. Vasisht & Gotthelf 1997; Woods et al. 1999; Gaensler et al. 1999). Below I briefly summarise these associations, then consider what these results tell us about AXPs, SGRs, and the relationship between the two populations.

2. Associations of SNRs with AXPs and SGRs

Claimed associations of SNRs with AXPs and SGRs are summarised in Table 1. Note that the association between SGR 1806–20 and G10.0–0.3 (Kulkarni et al. 1994) has been omitted, as the latter appears to be a synchrotron nebula powered by the SGR (or perhaps by some other source; Eikenberry, these proceedings) and gives no evidence for a supernova explosion at some point in the past.

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For each association, I have listed an estimated age and distance for the SNR. It should be noted that the $\Sigma - D$ relation is not a valid method of determining distances to individual SNRs (e.g. Green 1984), and that distances derived using this method should not be taken seriously. Age estimates for SNRs are also uncertain, and usually depend on assumptions about the ambient density.

The parameter β corresponds to the offset of a compact object from the apparent centre of its SNR, in units of the SNR radius (e.g. Shull et al. 1989). For example, $\beta = 1$ corresponds to an AXP or SGR sitting on the rim of its associated SNR. The column V_T refers to the implied transverse velocity of the pulsar, using the adopted age, distance and offset.

Table 1.   Associations of SNRs with AXPs and SGRs. Values in *italics* are representative, and do not correspond to measured quantities.

AXP/SGR	SNR	t_{SNR} (kyr)	d_{SNR} (kpc)	β	V_T (km s^{-1})	Ref.
1E 1841–045	Kes 73	2	7	<0.2	<500	1, 2
AX J1845–0258	G29.6+0.1	<8	*20*	<0.15	<500	3
1E 2259+586	CTB 109	~10	5	<0.25	<500	4, 5
SGR 0526–66	N 49	5	50	1	2900	6
SGR 1627–41	G337.0–0.1	5	11	2	800	7
SGR 1900+14	G42.8+0.6	*10*	*10*	~1.2	~1800	—

References for ages & distances: (1) Sanbonmatsu & Helfand (1992); (2) Vasisht & Gotthelf (1997); (3) Gaensler et al. (1999); (4) Green (1989); (5) Rho & Petre (1997); (6) Vancura et al. (1992); (7) Corbel et al. (1999)

2.1. Anomalous X-ray Pulsars

Associations between neutron stars and SNRs are usually judged on criteria such as agreement in age/distance, positional coincidence and evidence from proper motion. Distance estimates for AXPs have uncertainties $\gtrsim 50\%$, and there is no evidence that their characteristic ages ($\tau_c \equiv P/2\dot{P}$) are reliable age estimators. We also lack proper motion measurements for these sources, and so are left only with positional coincidence in order to judge associations.

In all three cases in Table 1, the AXP is sitting almost exactly at the centre of its SNR. The probability of random superposition is thus very small, <0.2% (see Gaensler et al. 1999), and we can conclude that all three AXPs are likely to be physically associated with their coincident SNRs. The upper limits on the AXPs' transverse velocities are entirely consistent with the velocity distribution seen for radio pulsars (e.g. Lyne & Lorimer 1994). Both the ages of the associated SNRs, and the values of β argue strongly that AXPs are young (<10 kyr) objects; the apparent absence of SNRs around the remaining three AXPs is consistent with the expectation that many (or even most) SNRs occur in low density regions, and do not produce detectable emission (Kafatos et al. 1980; Gaensler & Johnston 1995b). This result implies a Galactic birth-rate for AXPs of >0.6 kyr^{-1}, corresponding to at least 5% of core-collapse supernovae (see Gaensler et al. 1999).

2.2.   Soft Gamma-ray Repeaters

Just as for the AXPs, we cannot appeal to age, distance or proper motion in considering associations between SGRs and SNRs. Turning to positional coincidence, we find that all three SGRs are on the edge of, or outside, their coincident SNRs. The probability of a chance coincidence increases as β^2, and one consequently finds a substantially higher probability than for the AXPs that the SGR/SNR associations are spurious (e.g. Smith et al. 1999). Of the $\sim$10 claimed associations between SNRs and radio pulsars with $\beta > 1$, all but one is likely to be geometric projection (e.g. Gaensler & Johnston 1995a,b; Nicastro et al. 1996; Stappers et al. 1999).

Thus we are left to conclude either that the SGR/SNR associations are not genuine, or that SGRs have substantially higher velocities than do radio pulsars. There is currently no way to distinguish between these possibilities; using *Chandra* to measure the proper motion of the SGRs seems to be the only avenue by which this might be resolved. We note that Duncan & Thompson (1992) argue that the mechanism which forms a magnetar will indeed impart the neutron star with a high recoil velocity, consistent with the values of V_T for the SGRs in Table 1.

3.   Relationship between AXPs and SGRs

On the basis of the small value of τ_c for SGR 1806–20, Kouveliotou et al. (1998) have argued that SGRs eventually evolve into AXPs. Meanwhile, Gotthelf et al. (1999) appeal to the young age of the Kes 73/1E 1841–045 association to argue that AXPs evolve into SGRs! However, if all the associations in Table 1 are genuine, then AXPs and SGRs clearly have different velocity distributions and so cannot possibly be drawn from the same population, coeval or otherwise.

On the other hand, if one argues that the SGR/SNR associations in Table 1 are merely chance coincidence, then the corresponding estimates of V_T are invalidated. The absence of associated SNRs for SGRs would then imply that SGRs have ages $\gtrsim$50–100 kyr (e.g. Shull et al. 1989; Frail et al. 1994), and the data would then be consistent with AXPs evolving into SGRs. One possible problem with this scenario is that if one extrapolates the steady spin-down seen in several AXPs to such ages (Gotthelf et al. 1999; Kaspi et al. 1999), we would then expect SGRs to have periods $\gg$10 s, which is not observed.

4.   Conclusions

The three associations between AXPs and SNRs are all convincing, and indicate that AXPs are young ($<$10 kyr), low velocity neutron stars. The three SGR/SNR associations seem likely to be genuine, and rely on SGRs being high velocity ($>$1000 km s^{-1}) objects. If the SGR/SNR associations are indeed spurious, then SGRs can be explained as older manifestations of AXPs. However, if the SGR/SNR associations are shown to be real, then we must conclude that there is no evolutionary link between SGRs and AXPs. Possible alternatives are that AXPs are accreting systems as originally claimed (e.g. van Paradijs et al. 1995), or that there is more than one type of magnetar.

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